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*Indian Standard*

RECOMMENDED METHODS FOR THE  
DETERMINATION OF THE PERMITTIVITY  
AND DIELECTRIC DISSIPATION FACTOR  
OF ELECTRICAL INSULATING MATERIALS  
AT POWER, AUDIO AND RADIO FREQUENCIES  
INCLUDING METRE WAVELENGTHS

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INDIAN STANDARDS INSTITUTION  
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG  
NEW DELHI 110002

# Indian Standard

## RECOMMENDED METHODS FOR THE DETERMINATION OF THE PERMITTIVITY AND DIELECTRIC DISSIPATION FACTOR OF ELECTRICAL INSULATING MATERIALS AT POWER, AUDIO AND RADIO FREQUENCIES INCLUDING METRE WAVELENGTHS

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**IS : 4486 - 1967**

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# ***Indian Standard***

## **RECOMMENDED METHODS FOR THE DETERMINATION OF THE PERMITTIVITY AND DIELECTRIC DISSIPATION FACTOR OF ELECTRICAL INSULATING MATERIALS AT POWER, AUDIO AND RADIO FREQUENCIES INCLUDING METRE WAVELENGTHS**

### **0. FOREWORD**

0.1 This Indian Standard was adopted by the Indian Standards Institution on 25 November 1967, after the draft finalized by the Insulating Materials **Sectional** Committee had been approved by the Electrotechnical Division **Council**.

0.2 Insulating materials, solid as well as liquid, are used in general in two distinct ways :

- a) to support components of an electrical network and insulate them from each other and from ground, and
- b) as dielectric of a capacitor.

Especially when used for the function (b), it is important to know the properties, such as permittivity, dielectric dissipation factor, loss angle, etc.

0.3 This standard specifies different methods to measure these properties. These methods **are** suitable within different frequency limits. However, some of these methods may be used with special precautions for measurements at frequencies considerably lower or higher than the given limits.

0.4 In some cases, tests at voltages exceeding 1 000 V may introduce effects not related to permittivity and dielectric dissipation factor and are not included in this standard.

0.5 This standard is based on the IEC **Doc:15( Central Office)38 'Recommended Methods for the Determination of the Permittivity and Dielectric Dissipation Factor of Electrical Insulating Materials at Power, Audio and Radio Frequencies Including Metre Wavelengths'** prepared by International Electrotechnical Commission.

0.6 In reporting the result of a test made-in accordance with this standard, if the **final** value, observed or calculated, is to be rounded off, it shall be **done** in accordance with IS :2-1960\*

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\*Rules for rounding off numerical values (*revised*).

## 1. SCOPE

**1.1** This standard covers test methods for determination of permittivity and dissipation factor and of quantities calculated from them, such as loss index within the frequency range of 50 c/s to 300 Mc/s, of electrical insulating materials—liquid, fusible as well as solid materials.

## 2. TERMINOLOGY

**2.0** For the purpose of this standard, the following definitions shall apply.

**2.1 Relative Permittivity ( $\epsilon_r$ )** — It is the ratio of capacitance  $C_x$  of a capacitor in which the space between and around the electrodes is entirely and exclusively filled with the insulating material in question to the capacitance  $C_o$  of the same configuration of electrodes in vacuum:

$$\epsilon_r = \frac{C_x}{C_o} \quad \dots\dots\dots (1)$$

The relative permittivity  $\epsilon_r$  of dry air free from carbon dioxide, at normal atmospheric pressure equals 1.000 53, so that in practice the capacitance  $C_a$  of the configuration of electrodes in air may normally be used instead of  $C_o$  to determine the relative permittivity  $\epsilon_r$  with sufficient accuracy.

The *permittivity* of an insulating material in a measurement system is the product of its relative permittivity  $\epsilon_r$  and the electric constant ( or permittivity of vacuum )  $\epsilon_o$  in that measurement system.

In the SI system, the absolute permittivity is expressed in farad per metre ( F/m ); furthermore, in the rationalized SI system, the electric constant  $\epsilon_o$  has the following value:

$$\epsilon_o = 8.854 \cdot 10^{-12} \text{ F/m} \approx \frac{1}{36\pi} \times 10^{-9} \text{ F/m} \quad \dots\dots\dots (2)$$

For the purpose of this standard where picofarads and centimetres are used in calculating capacitance, the electric constant is  $\epsilon_o = 0.08854 \text{ pF/cm}$ .

**2.2 Dielectric Loss Angle ( $\delta$ )** — It is the angle by which the phase difference between applied voltage and resulting current deviates from  $\pi/2$  radian, when the dielectric of the capacitor consists exclusively of the insulating material.

**2.3 Dielectric Dissipation Factor ( $\tan \delta$ )** — It is the tangent of the loss angle  $\delta$ .

**2.4 Loss Index ( $\epsilon''$ )** — It is equal to the product of its dissipation factor,  $\tan \delta$ , and its relative permittivity,  $\epsilon_r$ .



**2.5 Relative Complex Permittivity ( $\bar{\epsilon}_r$ )** — It is derived by combining the relative permittivity and loss index.

$$\bar{\epsilon}_r = \epsilon'_r - j\epsilon''_r \quad \dots\dots\dots (3)$$

$$\epsilon'_r = \epsilon_r \quad \dots\dots\dots (4)$$

$\epsilon_r$  being the relative permittivity defined in 2.1.

$$\epsilon''_r = \epsilon_r \tan \delta \quad \dots\dots\dots (5)$$

$$\tan \delta = \frac{\epsilon''_r}{\epsilon'_r} \quad \dots\dots\dots (6)$$

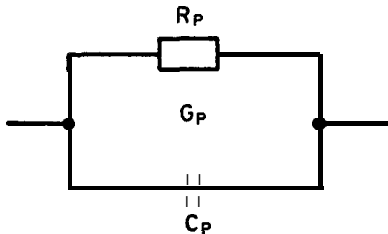
**NOTE —** A capacitor with losses may be represented at any given frequency either by capacitance  $C_s$  and resistance  $R_s$  in series or by capacitance  $C_p$  and resistance  $R_p$  (or conductance  $G_p$ ) in parallel.

While the parallel representation of an insulating material having a dielectric loss is usually the more proper representation, it is always possible and occasionally desirable to represent a capacitor at a single frequency by a capacitance  $C_s$  in series with a resistance  $R_s$ .

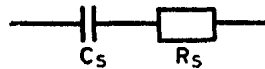
The dielectric dissipation factor  $\tan \delta$  is the same for the series and parallel representations.

The calculations given in this standard assume that measurements are made with a current having a sinusoidal wave shape and a frequency  $f$ . The diagram of equivalent parallel circuit and equivalent series circuit is given in Fig. 1.

**EQUIVALENT PARALLEL CIRCUIT**



**EQUIVALENT SERIES CIRCUIT**



**FIG. 1 EQUIVALENT PARALLEL CIRCUIT AND EQUIVALENT SERIES CIRCUIT**

$$\tan \delta = \frac{1}{\omega C_p R_p} = \frac{G_p}{\omega C_p} \quad \dots\dots\dots (7)$$

$$\tan \delta = \omega C_s R_s \quad \dots\dots\dots (a)$$

Between the series components and the parallel components the following relations hold:

$$C_p = \frac{C_s}{1 + \tan^2 \delta} \quad \dots\dots\dots (9)$$

$$R_p = \frac{1 + \tan^2 \delta}{\tan^2 \delta} R_s \quad \dots\dots\dots(10)$$

$$\omega C_s R_s = \frac{1}{4 R_p} \quad \dots\dots\dots(11)$$

In equation 7, normally  $\tan^2 \delta$  is very small compared to 1. If  $\tan^2 \delta$  cannot be ignored, the parallel capacitance shall be evaluated and this value used for calculating the permittivity.

### 3. FACTORS WHICH INFLUENCE THE DIELECTRIC PROPERTIES

**3.1** Frequency, temperature, field strength and impurities such as moisture, have considerable influence on the dielectric properties as described below.

**3.1.1 Frequency** -- Only a few materials, such as fused silica, polystyrene, or polyethylene, have  $\epsilon'$  and  $\tan \delta$  substantially constant over the wide frequency range through which dielectric materials are used for technical purposes, it is necessary to measure the loss angle and the permittivity at those frequencies at which the dielectric material is to be used.

Changes in permittivity and in dissipation factor are produced by the dielectric polarization and conductivity. The most important changes are caused by dipole polarization due to polar molecules and interfacial polarization caused by inhomogeneities in the material.

**3.1.2 Temperature** -- The loss index may show a maximum at a frequency which depends upon the temperature of the dielectric material. The temperature coefficients of dissipation factor and permittivity may be positive or negative depending on the position of the loss index maximum with respect to the measuring temperature.

**3.1.3 Moisture** -- The degree of polarization is increased by absorption of water or by the formation of a water film on the surface of the dielectric material, thus raising the permittivity, the dissipation factor and the dc conductivity. Conditioning of test specimens is, therefore, of decisive importance and control of the moisture content, both before and during testing, is imperative if test results are to be interpreted correctly.

**NOTE**—The gross effects of humidity usually occur at frequencies below approximately 1Mc/s and in the microwave frequency region.

**3.1.4 Field Strength** -- When interfacial polarization exists the number of free ions increases with the field strength, and the magnitude and the position of the loss index maximum is altered.

At higher frequencies, permittivity and dissipation factor are independent of the field strength so long as no ionization or corona occurs in voids in the dielectric.

## 4. SPECIMEN FOR SOLID MATERIALS

4.1 Specimens for solid material may be available in two forms:

- a) Sheet specimen, and
- b) Cylindrical tubular form.

For determining permittivity and dissipation factor sheet specimens are preferable. The influence of various dimensions on determination of these factors is discussed in 5.

NOTE — If the material is not in the forms (a) or (b) it should be reduced to one of these forms as far as practicable for the purpose of testing.

## 5. EFFECT OF THE SPECIMEN DIMENSIONS ON THE MEASURED DIELECTRIC PROPERTIES

5.1 Permittivity — When high accuracy is needed in measuring permittivity, the source of the greatest uncertainty is the dimensions of the specimen, thickness in particular and the area.

5.1.1 *Thickness* — The thickness should be large enough to allow its measurement with the required accuracy. The choice of thickness depends on the method of producing the specimen and the likely variation in thickness from point to point. For one percent accuracy, 1.5 mm is usually enough, although for greater accuracy it may be desirable to use a thicker specimen, for example, 6 to 12 mm.

5.1.1.1 The thickness shall be determined by measurements distributed systematically over the area of the specimen which is used in the electrical measurement, and should be uniform to within  $\pm 1$  percent of the average thickness. When the specimen electrodes extend to the edge of the specimen, the thickness may be determined by weighing, if the density of the material is known.

5.1.2 *Area*—The area chosen for the specimen should be such as to provide a specimen capacitance which may be measured to the desired accuracy. With well guarded and screened apparatus there need be no difficulty in measuring capacitances of 10 pF. Much existing apparatus, however, is limited in resolution to about one pF and then the specimen will need to be thin and of a diameter of 10 cm or more.

5.2 Dissipation Factor—When small values of dissipation factor are being measured, it is essential that the loss introduced by the series resistance of the leads be as small as possible, that is, the product of the resistance and the capacitance being measured should be as small as possible. Also, the ratio of the measured capacitance to the total capacitance should be as large as possible. The first point indicates a need for keeping the lead resistances as low as possible and the desirability of having a small specimen capacitance.

The second point indicates the need for low total capacitance in the arm of the bridge to which the specimen is connected and the desirability of having a large specimen capacitance. Probably the best compromise is a specimen having a capacitance of about 20 pF, used with a measuring circuit which does not connect more than about 5 pF in parallel with the specimen.

## 6. ELECTRODE SYSTEMS ON THE SOLID SPECIMEN

**6.1** Two types of electrode systems may be used on the solid specimen:

- a) Electrodes applied to the specimen, and
- b) Electrodes not applied directly on the specimen.

**6.1.1** *Electrodes Applied to the Specimen* — Electrodes of any one of the materials listed in 6.1.1.2 is applied to the surface of the specimen. When a guard ring is not used and when there is difficulty in locating electrodes accurately opposite one another on the two faces of the specimen, one electrode should be larger than the other. The specimen with its own electrodes shall then be mounted between metal backing electrodes, these being slightly smaller than the specimen electrodes. The equations for computing the capacitance of different arrangements of disk-shaped or cylindrical electrodes as well as empirical equations for computing the approximate edge capacitances for this condition are given in Appendix A. These equations hold only for a restricted range of shapes of specimens.

**6.1.1.1** For measurement of dissipation factor, electrodes of this type are unsatisfactory at high frequencies unless the surfaces of the specimen and the metal plates are very flat ( see 5.1.1.1 ). The electrode system of Fig. 2 also requires specimens to be of uniform thickness. ( The system in Fig. 2 also provides a built-in vernier capacitor for use in the reactance-variation method of measurement. )

### **6.1.1.2** *Electrode materials*

- a) *Metal foil electrodes* -- Metal foil electrodes may be applied to the specimen by using the smallest possible quantity of silicon grease or of any other suitable low-loss adhesive. The metal foil may be of:
  - 1) pure tin or lead or an alloy of these metals, of thickness up to 100 microns; and
  - 2) aluminium or gold of thickness 25 microns or less. Aluminium foils however are liable to form an electrically insulating oxide film which may influence the measuring results.
- b) *Fired-on metal electrodes* — Metal films may be fired on glass, mica and ceramics and are suitable for tests on these materials. Silver is commonly used, but migrates under a potential difference at high temperatures or high humidities. Gold is preferable.

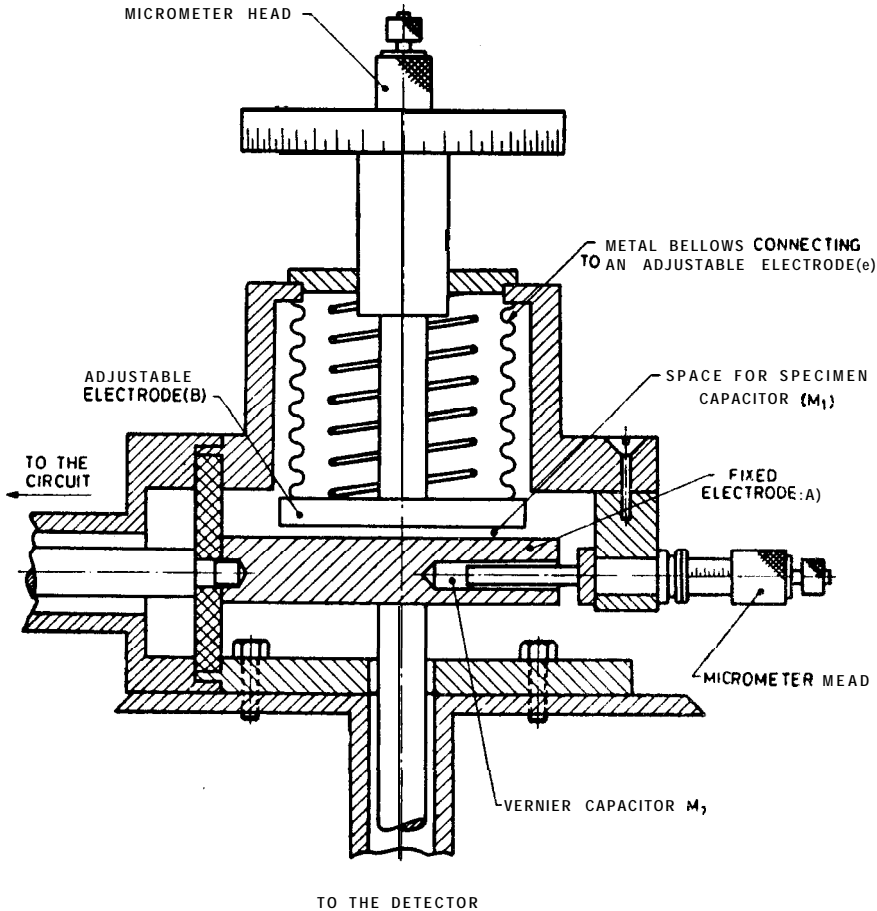


FIG. 2 MICROMETER CAPACITOR ASSEMBLY FOR SOLID DIELECTRICS

- c) **Electrodes produced by spraying metal** — Zinc or copper electrodes may be sprayed on to the specimen. They conform readily to a rough surface. They may be applied even to cloth since they do not penetrate very small holes.
- d) **Metal electrodes applied by cathodic evaporation or evaporation in high vacuum** — These procedures may be used if the resultant stresses neither change nor damage the insulating material, and if the material does not emit excessive gas when subjected to vacuum. The edges of any such electrodes shall be sharply defined.

- e) **Mercury and other liquid metal electrodes** — These may be used by clamping the specimen between suitable hollow blocks and filling with liquid **metal** which is clean. Mercury should not be used at high temperatures, and precautions should be taken even when using it at room temperature, as its vapour is toxic.

Woods metal or other low-melting alloy may be used in a similar manner. These alloys frequently contain cadmium which, like mercury, is a toxic element. These alloys should be used above 100°C only in a well-ventilated room or preferably in a hood and the staff told of the possible health hazards.

- f) **Conducting paint** — Certain types of high-conductivity silver paints, either air-drying or low-temperature-baking varieties, are commercially available for use as electrode material. They are sufficiently porous to permit diffusion of moisture through them and thereby allow the test specimen to condition after application of the electrodes. This is particularly useful in studying humidity effects. The paint has the disadvantage of not being ready for use immediately after application. It usually requires on overnight air-drying or low-temperature baking to remove all traces of solvent, which otherwise may increase both permittivity and dissipation factor.

The edges of any such electrodes shall be sharply defined; this may be difficult when the 'paint is brushed on, but this limitation may usually be overcome by spraying the paint and employing either clamp-on or pressure-sensitive masks. The conductivity of silver paint electrodes may be low enough to give trouble at the highest frequencies.

It is essential that the solvent of the paint has not permanent effect on the specimen.

- g) **Graphite** — Graphite is not recommended but may sometimes be used, especially at lower frequencies. Its resistance may cause an appreciable increase in loss angle and if it is applied from a suspension in a liquid it may penetrate the specimen.

**6.1.2 Electrodes Not Applied Directly on the Specimen** — Specimens of sufficiently low surface conductivity may be tested without applied electrodes by inserting them in an electrode system in which there is an intentional gap, occupied by air or liquid, on one or both sides of the specimen. The equations for computing the capacitances of arrangements of plane or cylindrical electrodes are given in Appendix B.

The test specimen should be a disk having the same diameter as the cell electrodes, or for micrometer electrodes, the specimen may be sufficiently smaller to render edge effects negligible. To make the edge effects negligible in the micrometer electrodes, the specimen diameter should be

smaller than that of the micrometer electrodes by at least twice the thickness of the specimen.

Equations for these special cases are given in Appendix B.

With this system, two forms of apparatus are recommended:

- a) *With micrometer-controlled parallel electrodes* — This equipment is normally used while making measurements in air. The capacitance may be adjusted to the same value with and without the specimen inserted, and the permittivity determined without reference to the electrical calibration of the measuring system.

A guard electrode may be included in the electrode system.

- b) *Fluid displacement method* — In a liquid whose permittivity is nearly equal to that of the specimen and whose dissipation factor is negligible, the measurement depends less critically than usual on exact knowledge of the thickness of the specimen. By using two fluids in turn, the thickness of the specimen and the dimensions of the electrode system may be eliminated from the equations.

**6.2 Elimination of Edge Effects in the Electrode Systems** — To avoid errors in permittivity caused by edge effects, the electrode system may include a guard electrode. If so, its width should be at least twice the thickness of the specimen, and the gap between it and the main electrode should be small compared with the thickness of the specimen. If guard rings cannot be used, a correction shall be made for edge capacitance ( see Appendix A). These equations are empirical and hold for only a restricted range of shapes of specimen.

6.2.1 Alternatively, the edge capacitance may be found from measurements both with and without a guard ring at some frequency at which this is convenient; the edge capacitance so found shall be sufficiently accurate for use as a correction at other frequencies and temperatures.

### 6.3 Choice Between the Two Types of Electrode Systems

6.3.1 The two important considerations are:

- a) *For sheet specimens*

- 1) *Ease of working* — Working without applied electrodes is quick and convenient, and avoids uncertainty about the effectiveness of the contact between electrodes and specimen.
- 2) The proportional error in permittivity

$$\frac{\Delta \epsilon_r}{\epsilon_r}$$

resulting from an error

$$\frac{\Delta h}{h}$$

in the measurement of thickness  $h$  is given by

$$\frac{\Delta \epsilon_r}{\epsilon_r} \frac{\Delta h}{h} \dots\dots\dots (12)$$

if electrodes are applied to the specimen, but if the specimen is placed between fixed electrodes it is given by:

$$\frac{\Delta \epsilon_r}{\epsilon_r} = \left( 1 - \frac{\epsilon_r}{\epsilon_f} \right) \frac{\Delta h}{h} \dots\dots\dots (13)$$

when  $\epsilon_f$  is the permittivity of the fluid in which the specimen is immersed, being unity for the measurement in air.:

- i) For non-porous materials having permittivities above about 10, deposited metal electrodes should be used. For such materials the electrodes should cover the whole surfaces of the specimen, and no guard electrode is necessary.
- ii) For materials having permittivities between about 3 and 10 the electrodes allowing the best accuracy are foils, mercury or deposited metal, and they shall be chosen to suit the properties of the material.
- iii) But if sufficient accuracy may be obtained in the measurement of thickness, the method with no electrodes applied to the specimen may be preferred for convenience.
- iv) The liquid-immersion method is excellent if suitable liquids exist and their permittivities are known or may be determined with sufficient accuracy.

**6.3.2 For Cylindrical Tubular Specimens** — The most appropriate electrode system for a tube specimen shall depend on its permittivity, wall thickness, diameter and the accuracy of measurement required. In general, the electrode system should consist of an inner electrode and a somewhat narrower outer electrode, with a guard electrode at each end. The gap between the outer and guard electrodes should be small compared with the thickness of the tube wall. For tube specimens of small and medium diameters, three bands of foil or deposited metal may be applied to the outside of the tube, the centre foil serving as the working outer electrode with the two bands of foil or deposited metal, one on each side, serving as guard electrodes. Inner electrodes of mercury, deposited metal film, or a tightly fitting mandrel may be used.

For tube specimens of high permittivity, the inner and outer electrodes may extend the complete length of the tube and the guard electrodes dispensed with.



For tubes or cylinders of large diameter the electrode system may be either circular or rectangular patch, a portion only of the tube periphery being tested. Such specimens may be considered as sheet specimens. Inner electrodes of metal foil, deposited metal film or a tightly fitting mandrel are employed with outer and guard electrodes of metal foil, or deposited metal. A flexible, expanding clamp may be necessary inside the tube to ensure satisfactory contact between the inner electrode and the specimen if a foil electrode is used.

- a) For very accurate measurements a system with no electrodes applied to the specimen may be used provided sufficient accuracy may be obtained in the measurement of thickness.
- b) For tube specimens having permittivities,  $\epsilon_r$ , up to 10, the most convenient electrodes are foils, mercury or deposited metal.
- c) For tube specimens having permittivities,  $\epsilon_r$ , above 10, deposited metal electrodes should be used for ceramic tubes. The electrodes may be applied to the complete circumference of the tube as bands or to only a portion of the circumference.

## 7. TESTING CELLS FOR LIQUID MATERIALS

**7.1 Design of Cells** — The essential features of an electrode system for testing liquids having low loss are that it may easily be cleaned, reassembled if necessary, and filled without disturbing the relative positions of the electrodes.

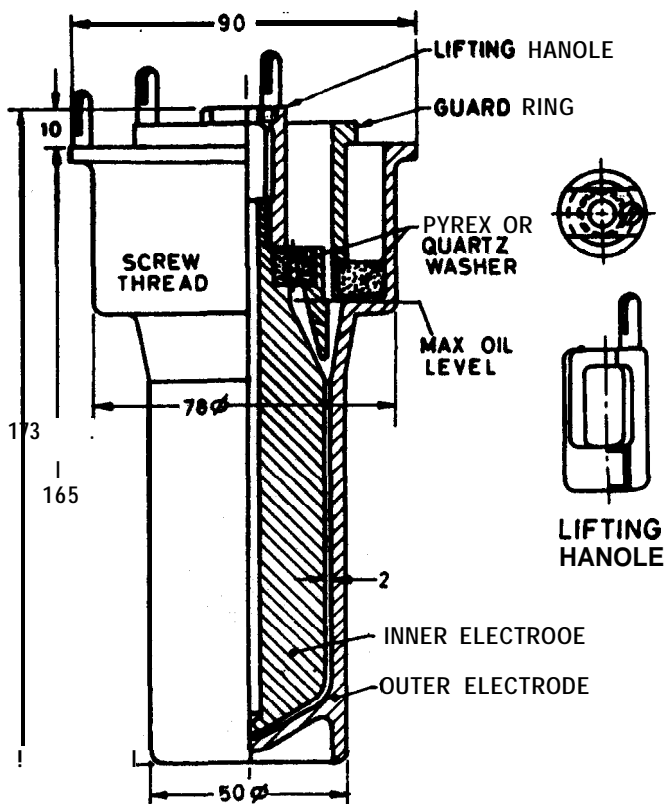
7.1.1 Other desirable features are:

- a) It should need only a small amount of liquid,
- b) Its temperature should be easily controllable,
- c) The terminals and connections should be adequately screened, and
- d) The insulating supports for the electrodes should not be immersed in the liquid.

Furthermore, the cell should not contain too short **creepage** distances and sharp edges which otherwise could influence the measuring accuracy.

Details of cells meeting the above requirements are given in Fig. 3 to 5. The electrodes are of stainless steel and the insulation of borosilicate glass (pyrex) or fused quartz.

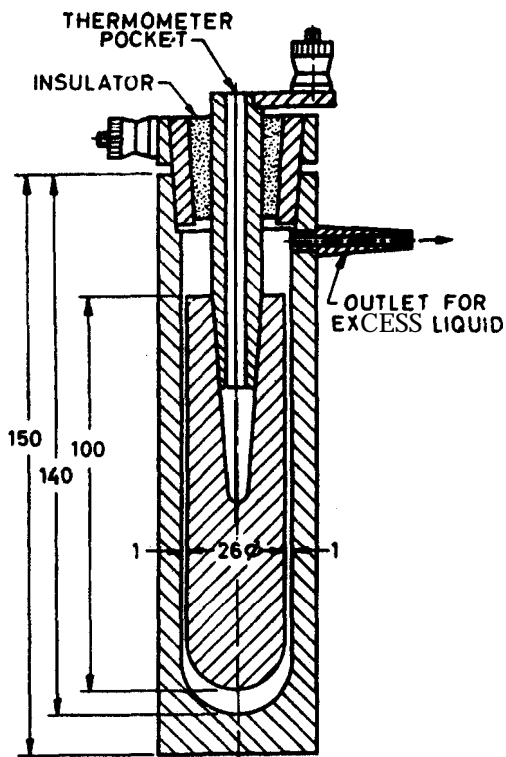
As some liquids, for example, chlorides, reveal some significant dependence of the dielectric dissipation factor on the electrode material, electrodes made of stainless steel are not appropriate in all cases. Much more stable results sometimes have been obtained working with electrodes made of aluminium and duraluminium.



All dimensions in millimetres.

FIG. 3 EXAMPLE OF A THREE-TERMINAL CELL FOR MEASUREMENTS ON LIQUIDS

79 Preparation of Cells — The cell should be cleaned with one or more appropriate solvents or a succession of solvents which have previously been checked to ensure that they do not contain unstable compounds, either by chemical tests for purity or by ascertaining that they lead to correct results on a sample liquid of known low permittivity and dielectric dissipation factor. When cells are used for testing some types of insulating fluids, it may be necessary to clean the electrode surfaces of the cell with a mildly abrasive detergent and water as the use of solvents alone does not always result in the removal of contamination products. If a series of solvents is used, it should end with the use of analytical grade petroleum ether with a maximum boiling point less than 100°C or, alternatively, with any solvent, the use of



( Quantity of liquid required to fill cell 15 ml approx. )

All dimensions in millimetres.

FIG. 4 EXAMPLE OF A TWO-TERMINAL CELL FOR MEASUREMENTS ON LIQUIDS

which has been shown to result in the correct values being obtained for a liquid of known low permittivity and dielectric dissipation factor and chemically similar to the liquid to be tested. The technique described below is recommended.

**7.2.1** The cell should be dismantled completely and all parts thoroughly cleaned with the chosen solvents either by a reflux procedure or repeated washings with agitation in a fresh solvent. All parts should be shaken free of solvent and placed in an uncontaminated oven at approximately 110 deg for 30 minutes.

The parts should be allowed to cool to a few degrees above room temperature and then reassembled. The cell should then be filled with

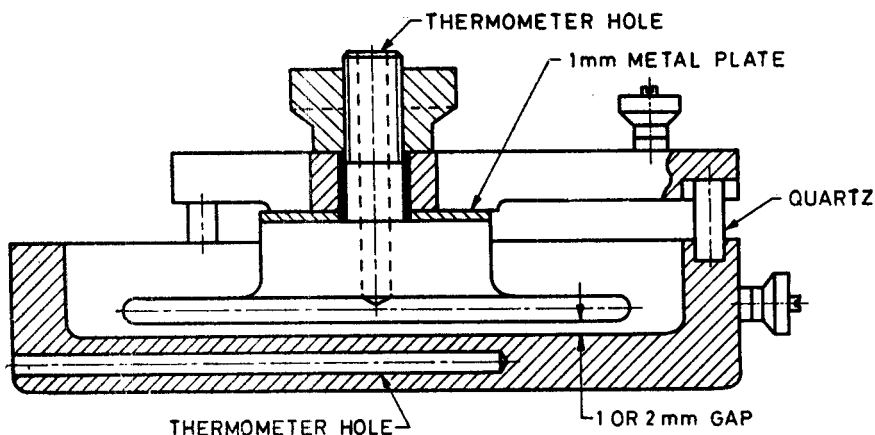


FIG. 5 TWO-TERMINAL CELL WITH PLANE ELECTRODES  
FOR MEASUREMENTS ON LIQUIDS

some of the liquid to be measured, allowed to stand for a few minutes, emptied and refilled. The supporting insulation should not be wetted by the liquid.

NOTE — During routine testing oils of the same quality the cleaning procedure described above may be replaced by merely rubbing the cell after each test with a dry paper which leaves no waste.

7.2.1.1 At all stages the parts should be manipulated with clean hooks or tongs so that no effective internal surfaces are touched with the hands.

7.2.2 Appropriate precautions against fire and toxic effects on personnel shall be observed when using solvents, like benzene, carbon tetrachloride, toluene and xylene which are particularly toxic. Further, chlorinated solvents are subject to decomposition by light.

## 8. CALIBRATION OF CELLS

8.1 When high accuracy in determining the dielectric permittivity of liquid dielectrics is needed, the 'electrode constant' should be determined preliminarily by means of a calibration liquid of known relative permittivity, for example, benzene.

The 'electrode constant'  $C_e$  is determined by the formula

$$C_e = \frac{C_n - C_o}{\epsilon_n - 1} \quad \dots\dots\dots(14)$$

where

$C_n$  = the capacitance of electrode arrangement filled with the calibration liquid;

$C_o$  = the capacitance of electrode arrangement, in air; and

$\epsilon_n$  = the relative permittivity of the calibration liquid.

The difference of values  $C_o$  and  $C_c$  gives the correction capacitance

$$C_g = C_o - C_c \quad \dots\dots\dots(15)$$

which is taken into account while calculating the relative permittivity  $\epsilon_x$  of the unknown liquid according to

$$\epsilon_x = \frac{C_x - C_g}{C_c} \quad \dots\dots\dots(16)$$

where

$C_x$  = the capacitance of electrode arrangement filled with the liquid to be tested.

Maximum accuracy in  $\epsilon_x$  is obtained if values  $C_o$ ,  $C_n$  and  $C_c$  are determined at that temperature for which the value  $\epsilon_n$  is known.

The application of the described method ensures sufficiently accurate results to be obtained in determining the relative permittivity of liquid dielectrics, as it eliminates errors made either because of parasitic capacitances or of inaccurate measurement of the value of the gap between the electrodes.

## 9. CHOICE OF METHODS FOR MEASURING CAPACITANCE AND ac LOSS

**9.0** Methods for measuring capacitance and ac loss may be divided into two groups :

- a) Null methods, and
- b) Resonance methods.

**9.1 Null Methods** — are used at frequencies up to about 50 Mc/s. For measurements of permittivity and loss angle, substitution techniques are used, that is, the bridge is balanced by adjustment mainly in one arm of the network, both with and without the specimen connected. The networks normally used are:

- a) Schering bridge;
- b) the transformer bridge ( that is, a bridge with ratio arms coupled by mutual inductance ). The transformer bridge has the advantage of allowing the use of a guard electrode without any additional components or operations. It has no disadvantages in comparison with the other networks: and
- c) the parallel-T.

**9.2 Resonance Methods** — may.. be used in the range 10 kc/s to several hundred Mc/s. They are invariably substitution methods. The method commonly used is that of reactance-variation. They cannot easily be adapted for use with guard electrodes.

**9.3 Examples of typical bridges and circuits** are given in Appendix C.

**NOTE**—This enumeration may by no means be complete. Further information describing the bridges and the methods for making the measurements may be found in the literature and also in pamphlets of the firms producing such apparatus.

**9.4** Below are given frequency range over which the methods may be employed:

<i>Sl NO.</i>	<i>Method</i>	<i>Recommended Range of Frequency</i>	<i>Form of Specimen</i>
1.	Schering bridge	Up to about 50 Mc/s	Sheet or tube
2.	Transformer bridge	15 c/s to 50 Mc/s	Sheet or tube
3.	Parallel-T networks	50 kc/s to 30 Mc/s	Sheet or tube
4.	Resonant-rise method	Up to 260 Mc/s	Sheet or tube
5.	Susceptance-variation method	10 kc/s to 100 Mc/s	Sheet or tube

## **10. TESTING PROCEDURE**

**10.1 Preparation of Specimens** — The specimen shall be cut from the solid material or prepared by an appropriately standardized technique in order to obtain a determined initial condition.

The subsequent measurement of thickness shall be made accurately with a tolerance of  $\pm (0.2 \text{ percent} + 0.005 \text{ mm})$ . The measuring points shall be distributed uniformly over the surface of the specimen. The effective area is also determined if necessary.

**10.2 Conditioning** — The specimen should be conditioned in accordance with IS : 2260-1963\*.

**10.3 Measurement** — Electrical measurements are made in accordance with the method employed. At frequencies of 1 Mc/s or more, care shall be taken that the inductance of connecting leads does not influence the results.

## **11. RESULTS**

**11.1 Relative Permittivity  $\epsilon_r$**  — The relative permittivity  $\epsilon_r$  of a specimen provided with its own electrodes is calculated according to

\*Recommendations for the conditioning and testing of electrical insulating materials.

equation (1). As the measured capacitance  $C'_x$  of a specimen without guard rings contains a small amount of edge capacitance  $C_e$ , the relative permittivity is

$$\epsilon_r \frac{C'_x - C_e}{C_o} \dots\dots\dots (17)$$

where  $C_o$  and  $C_e$  may be calculated from Appendix A. If necessary, corrections should be made similarly. For capacitance of the specimen to earth, capacitance between switch contacts and the difference between equivalent series and parallel capacitances.

Relative permittivity of specimens measured between micrometer electrodes or between non-contacting electrodes is calculated according to the appropriate equations of Appendix B.

**11.2 Dielectric Dissipation Factor  $\tan \delta$  —** The dielectric dissipation factor,  $\tan \delta$  shall be calculated from the measured values in accordance with the equations given for the particular measuring arrangement used.

**11.3 Accuracy** which may be expected from various methods is given in Appendix D.

**11.4 Test Report —** In the test report the following information shall be given when relevant:

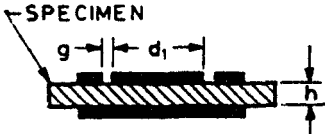
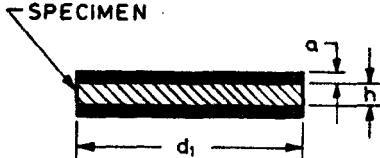
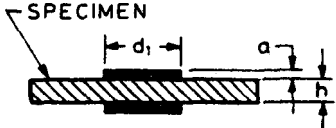
- a) Type and designation of the insulating material as well as the form in which it is delivered.
- b) Method of sampling, shape, dimensions of the test specimen and date of sampling ( statements on the specimen thickness and, if necessary, exact information on the treatment of the specimens at 'the contact areas of the electrodes are important ).
- c) Method and duration of conditioning the specimens.
- d) Electrode arrangement and type of adherent electrode, if used.
- e) Measuring apparatus.
- f) Temperature and relative humidity during the test and temperature of specimen.
- g) Applied voltage.
- h) Applied frequency...
- j) Relative permittivity  $\epsilon_r$  ( average value ).
- k) Dielectric dissipation factor  $\tan \delta$  ( average value ).
- m) Date of test.

**11.4.1** Values of relative permittivity and dielectric dissipation factor and the values calculated from them as loss index and loss angle shall be given if necessary, in relation to temperature and frequency. Not all are necessary or even appropriate in all cases.

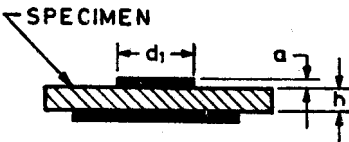
## APPENDIX A

(Clauses 6.1.1, 6.2, 11.1 and D-1.1)

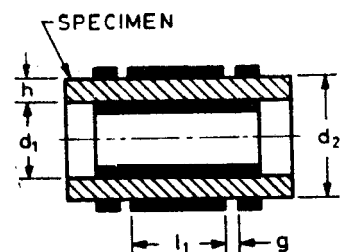
## CALCULATION OF VACUUM CAPACITANCE AND EDGE CORRECTIONS ATTACHED OR APPLIED ELECTRODES

TYPES OF ELECTRODES  (1)	DIRECT INTER-ELECTRODE CAPACITANCE UNITS: pF AND c m (2)	CORRECTIONS FOR EDGE CAPACITANCE UNITS: pF AND c m (3)
1. Disk electrodes with guard ring.  	$C_o = \epsilon_o \cdot \frac{A}{h}$ $= 0.08854 \cdot \frac{A}{h}$ $A = \frac{\pi}{4} (d_1 + g)^2$	$C_e = 0$
2. Disk electrodes without guard ring.		
a) Diameter of the electrodes = diameter of the specimen  	$C_o = \epsilon_o \cdot \frac{\pi}{4} \cdot \frac{d_1}{h}$	when $a < h$ $\frac{C_e}{P} = 0.029 - 0.058 \log h$ $P = \pi d_1$
b) Equal electrodes smaller than the specimen  	$= 0.06954 \frac{d_1^2}{h}$	$\frac{C_e}{P} = 0.019 \epsilon_1 - 0.058 \log h + 0.010$ $P = \pi d_1$ where $\epsilon_1$ is an approximate value of the specimen relative permittivity, and $a < h$

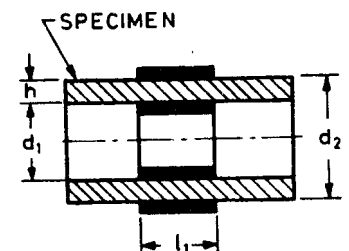


TYPES OF ELECTRODES	DIRECT INTER-ELECTRODE CAPACITANCE UNITS: pF AND C m	CORRECTIONS FOR E W E CAPACITANCE UNITS: pF AND C m
(1)	(2)	(3)
c) Unequal electrodes 	$C_o = \epsilon_o \cdot \frac{\pi}{4} \cdot \frac{d_1^2}{h}$ $= 0.069\ 54 \frac{d_1^2}{h}$	$\frac{C_e}{P} = 0.041 \epsilon_1 - 0.077$ $\log h + 0.045$ $P = \pi d_1$ where $\epsilon_1$ is an approximate value of the specimen relative permittivity, and $a < h$

## 3. Cylindrical electrodes with guard ring.

	$C_o = \epsilon_o \cdot \frac{2\pi (l_1 + g)}{l_n d_2/d_1}$ $= 0.2416 \frac{(l_1 + g)}{\log d_2/d_1}$	$C_e = 0$
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## 4. Cylindrical electrodes without guard ring.

	$C_o = \epsilon_o \cdot \frac{2\pi l_1}{l_n d_2/d_1}$ $= 0.241\ 6 \frac{l_1}{\log d_2/d_1}$	If $\frac{h}{h + d_1} < \frac{1}{10}$ $\frac{C_e}{P} = 0.019 \epsilon_1 - 0.058$ $\log h + 0.010$ $P = \pi (d_1 + h)$ where $\epsilon_1$ is an approximate value of the specimen relative permittivity
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Relative permittivity of specimen:

$$\epsilon_r = \frac{C'_x - C_e}{C_o}$$

where

 $C'_x$  = measured capacitance between electrodes, $l_n$  = natural logarithms, and

log = common logarithm.

## APPENDIX B

### ( Clauses 6.1.2, 11 .1 and C-6.2.2 )

#### CALCULATION OF SPECIMEN CAPACITANCE OF CONTACTING MICROMETER ELECTRODES AND RELATIVE PERMITTIVITY AND DISSIPATION FACTOR OF NON-CONTACTING ELECTRODES

##### B-1. CALCULATION OF SPECIMEN CAPACITANCE OF CONTACTING MICROMETER ELECTRODES

22	SPECIMEN CAPACITANCE (1)	REMARKS (2)	DEFINITION OF SYMBOLS (3)
	1) Substitution of the specimen capacitance by a standard capacitor in parallel.		$C_p$ = parallel Capacitance of the specimen
	$C_p = \Delta C - C_r + C_{or}$	Specimen diameter is less than the micrometer electrode diameter by at least 2 $r$ . The true thickness $t$ and area $A$ of the specimen shall be used in calculating the permittivity.	$\Delta C$ = increase of the capacitance of the standard capacitors as to restore balance after removal of the specimen  $C_r$ = calibration capacitance of the micro meter electrodes a spacing $r$

- 2) Substitution of the specimen **capacitance** by lowering the spacing of the micrometer electrodes after removal of the specimen.

$$C_p = C_s - C_r + C_{or}$$

Specimen diameter is less than the micrometer electrodes diameter by at least  $2r$ . The true thickness  $t$  and area  $A$  of the specimen shall be used in calculating the permittivity.

- 3) The double calculation of the air capacitance may be avoided with only small error ( 0.2 to 0.5 percent due to fringing at the electrode edge ), when the specimen has the same diameter as the electrodes by substitution of the specimen capacitance by a standard capacitor in parallel.

$$C_p = \Delta C - C_t + C_{ot}$$

Specimen diameter equals micrometer electrode diameter. Electrodes attached to the specimen are of zero thickness.

$C_s$  = calibration **capacitance** of the micrometer electrodes at spacing  $s$ , restoring balance after removal of the specimen

$C_t$  = **calibration** capacitance of the micrometer electrodes at spacing  $t$

$C_{or}$  = **air** capacitance for the area between the micrometer electrodes which was occupied by the specimen, at spacing  $r$  or  $t$  respectively, calculated using equation 1 of Appendix A

$r$  = thickness of specimen and applied electrodes

$t$  = thickness of specimen

Relative Permittivity

$$\epsilon_c = \frac{C_p}{C_o}$$

## B-2. CALCULATION OF RELATIVE PERMITTIVITY AND DISSIPATION FACTOR OF NON-CONTACTING ELECTRODES

RELATIVE PERMITTIVITY (1)	DISSIPATION FACTOR (2)	DEFINITIONS OF SYMBOLS (3)
1) Micrometer electrodes in air		$\Delta C$ = capacitance change when specimen is inserted ( + when capacitance increases ) $C_1$ = capacitance with specimen in place $c, = \epsilon_r . C_o$ = capacitance with fluid alone $C_o$ = vacuum capacitance for area considered ( $= \epsilon_o . A / h_o$ ) $A$ = area of one face of specimen in square centimetres (or area of electrodes when specimen is exactly the same size or larger than the electrodes ) $d_o$ = outer diameter of inner electrode
$\epsilon_r = \frac{1}{1 - \frac{\Delta C}{C_1} \cdot \frac{h_o}{h}}$ <p>or, if <math>h_o</math> is adjusted to a new value <math>h_o'</math>, such that <math>\Delta C = 0</math></p> $\epsilon_r = \frac{h}{h - (h_o - h_o')}$	$\tan \delta_x = \tan \delta_o + M . \epsilon_r . \Delta \tan \delta$	

## 2) Plane electrodes -fluid displacement

$$\epsilon_r = \frac{\epsilon_f}{1 + \tan^2 \delta_x}$$

$$\tan \delta_x = \tan \delta_c + M \cdot \Delta \tan \delta$$

$$\left\{ \frac{(C_f + \Delta C)(1 + \tan^2 \delta_c)}{C_f + M[C_f - (C_f + \Delta C)(1 + \tan^2 \delta_c)]} \right\} \left\{ \frac{(C_f + \Delta C)(1 + \tan^2 \delta_c)}{C_f + M[C_f - (C_f + \Delta C)(1 + \tan^2 \delta_c)]} \right\}$$

When the dissipation factor of the specimen is less than about 0.1, the following equations may be used:

$$\epsilon_r = \frac{\epsilon_f}{1 - \frac{\Delta C}{\epsilon_f C_o + \Delta C} \cdot \frac{h_o}{h}}$$

$$\tan \delta_x = \tan \delta_c + M \frac{\epsilon_r}{\epsilon_f} \cdot \Delta \tan \delta$$

## 3) Cylindrical electrodes-fluid displacement (for $\tan \delta_x$ less than about 0.1)

$$\epsilon_r = \frac{\epsilon_f}{1 - \frac{\Delta C}{C_1} \frac{\log d_3/d_o}{\log d_2/d_1}}$$

$$\tan \delta_x = \tan \delta_c + \Delta \tan \delta \cdot \frac{\epsilon_r}{\epsilon_f}$$

$$\left[ \frac{\log d_3/d_o}{\log d_2/d_1} - 1 \right]$$

## 4) Two-fluid method-plane electrodes (for $\tan \delta_x$ less than about 0.1)

$$\epsilon_r = \epsilon_{f1} + \frac{\Delta C_1 C_2 (\epsilon_{f2} - \epsilon_{f1})}{\Delta C_1 C_2 - \Delta C_2 C_1}$$

$$\tan \delta_x = \tan \delta_{C1} + \frac{\epsilon_r C_o - C_1}{\Delta C_2} \cdot \Delta \tan \delta_2$$

$d_1$ =inner diameter of specimen

$d_2$ =outer diameter of specimen

$d_3$ =inner diameter of outer electrode

$h_o$ =parallel-plate spacing

$h$ =average thickness of specimen

$M=h_o/h-1$

$\log$ =common logarithm

$\epsilon_f$ =relative permittivity of fluid at test temperature (= 1.00 for air)

$\epsilon_o$ =electric constant rated in pF/cm

$\Delta \tan \delta$ =increase in dissipation factor when specimen is inserted

$\tan \delta_c$ =dissipation factor with specimen in place

$\tan \delta_x$ =calculated dissipation factor of specimen

NOTE — In the equation for the two-fluid method, subscripts 1 and 2 refer to the first and second fluids, respectively.

## APPENDIX C

### ( Clause 9.3 )

#### APPARATUS

##### C-1. GENERAL

**C-1.1** In the methods given in C-2 to C-6 the following consideration apply.

##### C-1.2 Screening of Apparatus

C-1.2.1 An earthed screen between two points in the apparatus removes any capacitance between them and substitutes capacitance to earth from both of them. Screening of wires and components may therefore be used freely in circuits in which capacitance to earth from any point is unimportant; the **schering** bridge with wagner earth, and the transformer bridge, are circuits of this kind.

On the other hand, screening is unnecessary in a substitution bridge in parts of the circuit which remain unaltered whether the specimen is in or out.

In practice these two considerations imply that leads to the specimen, to the oscillator, and to the detector, should be screened. As much as possible, the apparatus should be enclosed within a metal screen to prevent variation in capacitance between the observer's body ( which may not be at earth potential, and may not remain stationary ) and the components of the bridge circuit.

C-1.2.2 For frequencies of the order of 100 kc/s or more, 'go' and 'returns' leads should be kept close together, so as to minimize self and mutual inductances; and if several wires are intended to be connected together, they should meet as nearly as possible at a single point, since the impedance of even a short length of wire may be appreciable at these frequencies.

C-1.2.3 If a switch is used to disconnect the specimen, it shall be such that the capacitance between its contacts when they are open does not cause an error in the measurement. In three-terminal measuring systems this may be achieved either by inserting an earthed screen between the contacts; or by using two switches in series and, when they are opened, earthing the connection between them; or by earthing the electrode which would otherwise be left disconnected.

##### C-1.3 Oscillators and Detectors for Bridges

**C-1.3.1 *ac* Voltage Sources** -The generator may be any source of power capable of supplying the necessary voltage and current with a total harmonic content of less than 1 percent.

**C-1.3.2 Detectors** — The following forms of detector are available. All may be used with an amplifier to increase the sensitivity:

- a) Telephone ( with frequency changer, if necessary );
- b) Electronic voltmeter or wave analyser;
- c) Cathode-ray oscillograph;
- d) ' Magic eye ' tuning indicator; and
- e) Vibration galvanometer ( for low frequencies only ).

A transformer may be needed between bridge network and the detector, either to match their impedances or because either side of the bridge output is grounded.

Harmonics may obscure or change the balance-point. This trouble may be avoided either by tuning the amplifier or by introducing a low-pass filter. A discrimination of 40 dB against the second harmonic of the measuring frequency is adequate.

## C-2. SCHERING BRIDGE

**C-2.1** The schering bridge represents the most classical device for the measurement of permittivity and dielectric losses. It is used in the frequency range from below power frequencies ( 50 and 60 c/s ) up to the order of 100 kc/s and for capacitances of 50 to 1 000 pF ( usual capacitances of specimens or equipment to be tested ).

**C-2.2 Description** — It is a four-arm network ( Fig. 6 ), two of these arms being primarily capacitive ( the unknown capacitance  $C_X$  and a capacitance  $C_N$  without losses ) and the two others ( often called measuring arms ) consisting of non-reactive resistances  $R_1$  and  $R_2$ , the resistance ( $R_1$ ) opposite to the unknown capacitance  $C_X$ , at least, being shunted by a capacitance ( $C_1$ ). This last capacitance, and generally one at least of the two resistances  $R_1$  and  $R_2$  are adjustable.

If one chooses for the capacitance  $C_X$  the equivalent representation of a resistance  $R_S$  and a ( pure ) capacitance  $C_S$  in series, the balance of the bridge illustrated in Fig. 6 leads to:

$$C_S = C_N \frac{R_1}{R_2} \quad \dots\dots\dots (18)$$

$$\text{and } \tan \delta_X = \omega C_S R_S = \omega C_1 R_1 \quad \dots\dots\dots (19)$$

If the resistance  $R_2$  is shunted by a capacitance  $C_2$ , the expression for  $\tan \delta$  becomes

$$\tan \delta_X = \omega C_1 R_1 - \omega C_2 R_2 \quad \dots\dots\dots (20)$$

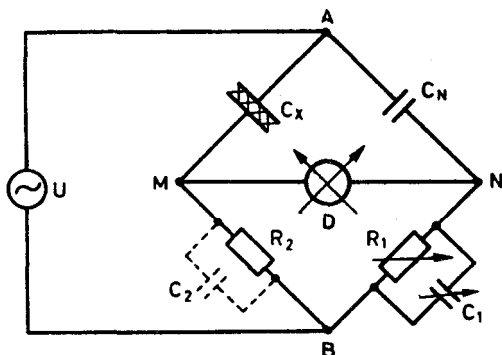


FIG. 6 SCHERING BRIDGE CIRCUIT DIAGRAM

C-2.3 The practical realizations of the bridge differs appreciably according to the frequency range. This is a result of the fact that a capacitance of 50 to 1 000 pF represents an impedance of about 60 to 3 megohms at 50 c/s and only about 30 000 to 1 500 ohms at 100 kc/s.

In the latter case, the four arms of the bridge may easily have impedances of the same order of magnitude, while this will never be the case at frequencies of 50 or 60 c/s. Thus two different types of bridges for use at low and at ( relatively ) high frequency may be distinguished.

C-2.4 This will normally be a high voltage, not only for reasons of sensitivity but also due to the fact that, at low frequencies, it is high voltage technology which is nearly exclusively interested in the problem of dielectric losses. The very great difference in the order of magnitude of the impedances between the so-called capacitive and measuring arms, consequently, results in a similar inequality in the distribution of the voltage, by far the largest part of it being found across the capacitances  $C_X$  and  $C_N$ . The balance conditions given above are only valid if the low voltage elements are screened from the high voltage elements, this screening shall be earthed in order to secure the stability of the balance. As Fig. 7 shows, the screening is compatible with the use of guarded capacitances  $C_X$  and  $C_N$ , the guard for  $C$  being practically indispensable.

The choice for the earthing procedure substantially leads to two types of bridges.

C-2.4.1 Simple *Schering Bridge with Screening-Point* B of the bridge ( supply terminal of the bridge on the side of the measuring arms ) is connected to the screening and to earth.

The screening acts well as a protection towards the high voltage side but it increases the capacitance between it and the various conductors leading



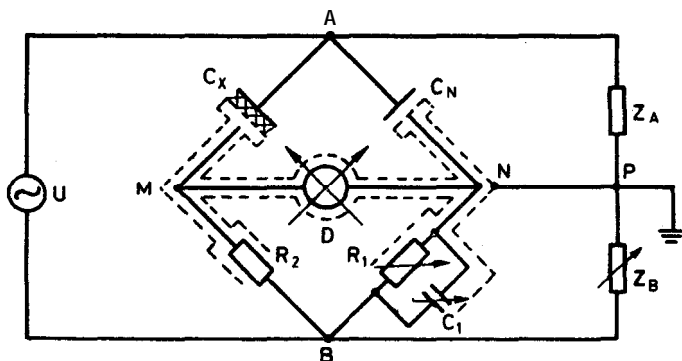


FIG. 7 SCHERING BRIDGE WITH WAGNER EARTH CIRCUIT

to the terminals *M* and *N* of the detector arm, this capacitance being subjected to the voltage across the measuring arms. This may introduce an error which normally limits the accuracy on  $\tan \delta$  to the order of 0.1 percent, especially when capacitances  $C_X$  and  $C_N$  are unequal.

**C-2.4.2 Schering Bridge with Wagner Earth Circuit** — In the bridge shown in Fig. 7 the detector arm and the screening are brought to the same potential. This is secured by using additional external arms  $Z_A$  and  $Z_B$  (wagner earth circuit) and the intermediate point *P* being connected to the screening and to earth. The additional arms (practically  $Z_B$ ) are adjusted in order that the voltages across  $Z_A$  and  $Z_B$  are identical to these across the capacitive and measuring arms of the bridge respectively. It is obvious that the solution consists in the simultaneous balance of two bridges, the main bridge *AMNB* and the auxiliary bridge *AMPB* (or *ANPB*). The double balance is reached by successive approximations, the detector being displaced from one to the other bridge. With this method, one order of magnitude may be gained on the accuracy, which is now in practice only limited by the precision of the elements used for the bridge.

It may be noted that the particular solution which has been considered requires that both terminals of the supply may be insulated from earth. If this is not possible, the use of a more complex arrangement is required (bridge with double screen).

**C-2.5 Schering Bridge for High Frequencies** — This bridge is normally operated with moderate voltages and is thus more flexible; the capacitance  $C_N$  very often is adjustable (while for high voltages, this capacitance is ordinarily of fixed value) and substitution methods may be more easily adopted.

Screening and wagner earth circuit may still be used with advantage as undesirable capacitive effects increase with the frequency.

**C-2.6 Detectors** — When point B of the schering bridge is earthed, detectors with asymmetrical input ( which are most common with electronic devices ) shall be avoided.

Such detectors, however, are readily used with bridges with a **wagner** earth circuit provided that the earthed input terminal be always connected to point **P**.

### C-3. TRANSFORMER BRIDGE ( INDUCTIVE RATIO-ARM BRIDGES )

C-3.1 The great advantage of the transformer bridge over the schering bridge is to allow a direct and rational earthing of the screens and guard electrodes without any need of additional auxiliary arms.

C-3.2 This bridge is based on a simpler principle than the schering bridge. Its fundamental arrangement is given in Fig. 8. When balanced, the ratio between the ( complex ) impedances  $Z_X$  and  $Z_M$  is identical to the ( vector ) ratio of voltages  $U_1$  and  $U_2$ . If this last ratio be known, then  $Z_X$  is readily derived from the knowledge of  $Z_M$ . In the ideal bridge, this ratio  $U_1/U_2$  is a pure number  $k$  and thus  $Z_X = k Z_M$ ; in particular, the argument of  $Z_N$  yields directly  $\delta X$ .

C-3.2.1 The bridge is used from power frequencies up to radio frequencies of several tenths of Mc/s; this range is thus wider than the previous one for the schering bridge but, again, the realization will differ appreciably according to the frequency range involved.

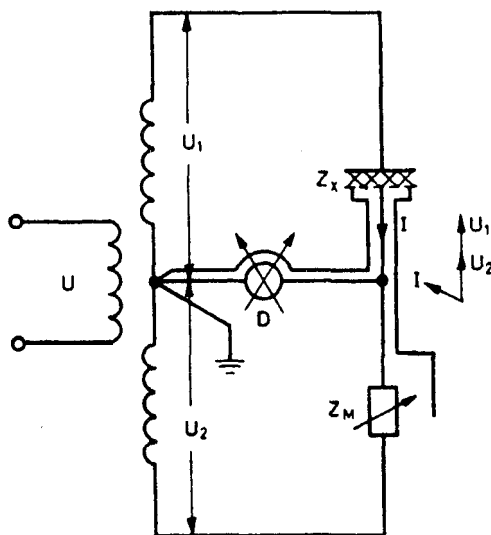


FIG. 8 TRANSFORMER BRIDGE CIRCUIT DIAGRAM

**C-3.3 Low Frequency Transformer Bridge** — This is a high voltage bridge ( more precisely, the voltage  $U_1$  is high while the voltage  $U_s$  remains moderate) and its technique is related to that of voltage transformers.

c-3.3.1 **Methods of Supply** — Two methods of supply are used:

- a) The supply voltage is directly applied to one of the windings, the other working as the secondary of a transformer, and
- b) The supply voltage is applied to a separate primary winding while both windings of the bridge itself constitute either two separate secondary circuits or a single secondary winding with an intermediate tapping allowing both voltages  $U_1$  and  $U_s$  to be obtained ( see Fig. 8 ).

C-3.3.2 **Calibration** — As with any measuring transformer, the bridge shows errors ( that is, the vector ratio  $U_1/U_2$  differs from its theoretical value ) and these errors are load dependant. The most important is the phase error between voltages  $U_1$  and  $U_2$  which influence directly the measurement of  $\tan \delta$ . It is thus necessary to calibrate the bridge. It is done by replacing  $Z_X$  by a capacitance  $C_N$  without losses ( similar to that used in the *schering bridge* ). If  $C_N$  has the same value as  $C_X$ , the method is practically a substitution and the calibration is immediate. But, as  $C_N$  is seldom adjustable, such a calibration would not remain valid for  $C_X$  on account of the load variation. It is then possible to operate under constant load ( see Fig. 9 ). A switch connects  $C_X$  to earth when  $C_N$  is measured and *vice versa*. The constant load for the high voltage winding is then the sum of both. ( A similar disposition should be used on the low voltage side but, because the loads are much smaller, such an arrangement, although easy to use, is less essential. )

C-3.3.2.1 When the calibration is made with a pure capacitance  $C_N$  connected across the voltage  $U_1$ , the measuring impedance  $Z_M$ , subjected to the voltage  $U_2$ , consists of either:

- a) a *pure* capacitance  $C_M$  if  $U_2$  and  $U_1$  have *the same phase* ( ideal case );  
or
- b) a capacitance  $C_M$  and a resistance  $R_M$ , if the voltage  $U_2$  is *leading* on the voltage  $U_1$ ; or
- c) in case the voltage  $U_2$  is *lagging* with respect to  $U_1$ , this resistance  $R_M$  should become negative. Therefore, in order to restore balance, a resistive component of the current has to be introduced on the side of  $U_1$ . But, as very high and adjustable resistors for high voltage practically do not exist, this resistive component is usually obtained through an auxiliary winding supplying a voltage  $U_3$  ( of low value ) in phase with  $U_1$  ( see Fig. 10 ).

**NOTE** — The addition of a resistance in series with  $C_N$  is impossible for the following reasons: if it were inserted below the capacitor, the potentials of the measuring electrode and of the guard of  $C_N$  would no longer be the same; and if inserted before  $C_N$  on the high voltage conductor, the current in the resistance also includes the ' guard circuit current and no calibration is possible.

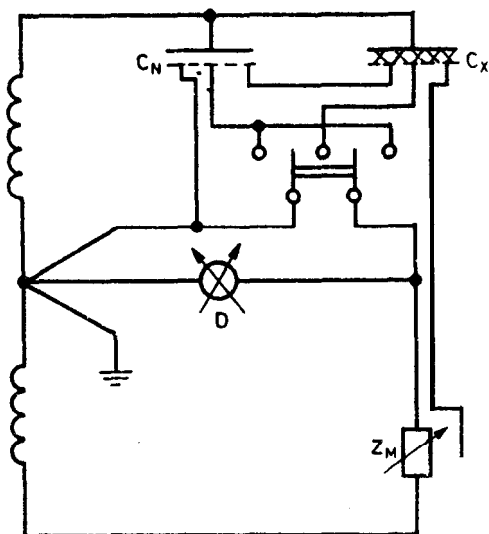


FIG. 9 TRANSFORMER BRIDGE CONSTANT LOAD CALIBRATION

These remarks may also be applied to the resistance  $R_M$  mentioned above for the second case. But on the low voltage side, a resistance of high and adjustable value shunting the capacitance may easily be obtained by using the star connection of three resistances  $R_1$ ,  $R_2$  and  $R'$  illustrated in dotted lines at bottom of Fig. 10. One has then:

$$R_M = R_1 + R_2 + \frac{R_1 R_2}{R'} \quad \dots\dots\dots (21)$$

The adjustable capacitance  $C_M$  for the measurement shall be a pure one or of low and well-known losses ( while the measuring capacitance  $C_1$  of the schering bridge does not have to comply with such severe conditions ).

**C-3.4 High Frequency Transformer Bridge** — Several of the previous considerations shall apply again but as the bridge shall normally no longer be a high voltage one, the arm across voltage  $U_1$  may easily admit adjustable elements and substitution methods, which are highly recommendable whenever applicable, may be readily used.

A bridge with separate primary winding allows the source and detector to be interchanged and the balance corresponds to the compensation of the opposite ampere-turns in the secondary windings.

**C-3.5 Detectors** — Due to the fact that one terminal of the detector arm is always earthed, the use of detectors with a symmetrical input is not required,



Then the capacitance of the specimen equals the decrease  $\Delta C_V$  of  $C_V$ .  
The conductance  $G$  of the specimen is:

$$G = \frac{\omega^2 C_A C_N R_T}{C_B} \cdot \Delta C_H \quad \dots\dots\dots (24)$$

and the dissipation factor  $\tan \delta$  of the specimen:

$$\tan \delta = \frac{\omega C_A C_N R_T}{C_B} \cdot \frac{\Delta C_H}{\Delta C_V} \quad \dots\dots\dots (25)$$

where  $\Delta C_H$  is the increase of  $C_H$

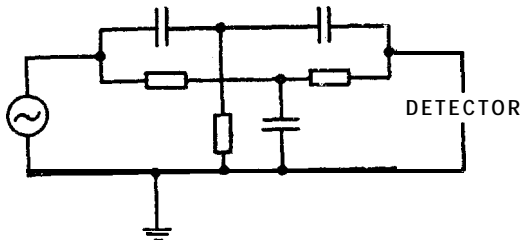


FIG. 11 PARALLEL-T NETWORK-PRINCIPAL CIRCUIT DIAGRAM

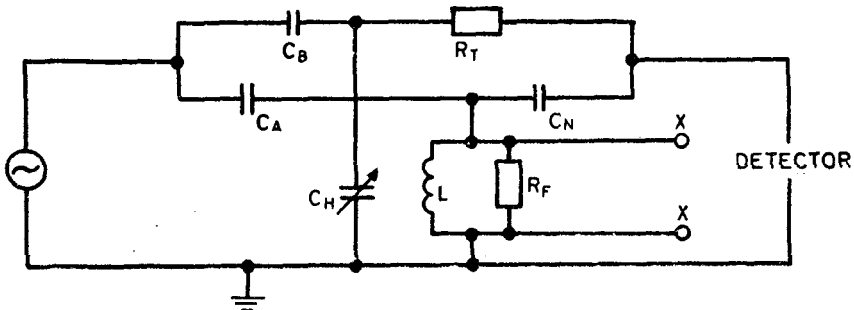


FIG. 12 PARALLEL-T NETWORK-PRACTICAL CIRCUIT DIAGRAM

C-4.4 These networks may conveniently be constructed for the frequency range of 50 kc/s to 50 Mc/s and are easy to screen satisfactorily. A serious disadvantage is that the balance is strongly sensitive to frequency, so that harmonics of the supply frequency are badly unbalanced. To cover a wide range of frequencies, components shall be changed or switched. At the highest frequencies the impedances of connecting wires and of switches ( if used ) may introduce significant errors.

## C-5. RESONANT-RISE ( Q-METER ) METHOD

**C-5.1** The method is based on measurement of the voltage appearing across a resonant circuit when a small known **voltage** is induced in it.

C-5.2 Figure 13 shows the usual form of the circuit, in which the resonant circuit is coupled to the oscillator by means of a common resistance  $R$ . Other methods of coupling are equally acceptable. The input voltage or current is adjusted at the required frequency, to a known value; the resonant circuit is tuned to its maximum response, voltage  $V_o$  is observed. The specimen is then connected to the appropriate terminals, the circuit brought again to its maximum response by adjusting the variable capacitor, and the new value of voltage,  $V_1$ , is observed.

When the specimen is connected and the circuit re-tuned, the total capacitance remains nearly constant, provided that  $R_L G \ll 1$  (see Fig. 13). The capacitance of the specimen is therefore approximately  $\Delta C$ , the change of capacitance of the variable capacitor.

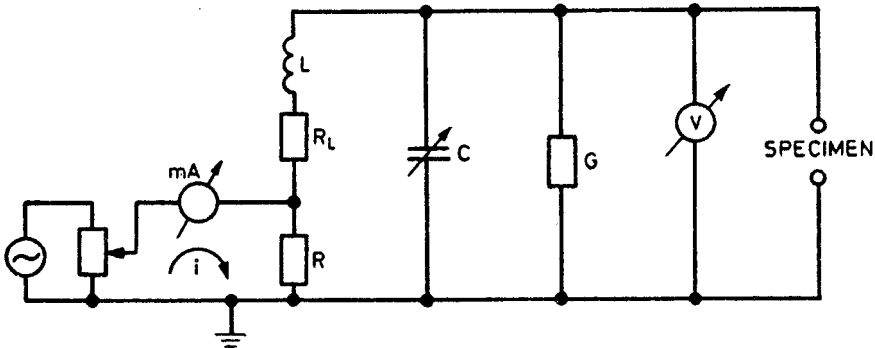
The dissipation factor of the specimen is approximately

$$\tan \delta \approx \frac{C_t}{\Delta C} \left( \frac{1}{Q_1} - \frac{1}{Q_o} \right) \dots\dots\dots (26)$$

where

$C_t$  is the total capacitance in the circuit including that of the voltmeter and the self-capacitance of the inductor, and

$Q_1, Q_o$  are the values of  $Q$  respectively with and without the specimen connected.



**FIG. 13** CIRCUIT DIAGRAM FOR RESONANT-RISE ( Q-METER ) METHOD

**C-5.3** The main sources of error in the method are in the calibrations of the two indicating instruments and in the unwanted impedances introduced in the wiring, especially between the variable capacitor and the specimen. For high values of dissipation factor the condition  $R_L G \ll 1$  may not hold, and the approximate equation quoted above then fails.

**C-5.4** The resonant-rise (**Q-meter**) method is used in the frequency range 10 kc/s to 260 Mc/s.

## C-6. SUSCEPTANCE VARIATION METHOD ( REACTANCE-VARIATION METHOD )

**C-6.1 General** -- The micrometer electrode system as shown in Fig. 2 was developed by Hartshorn to eliminate the errors caused at high frequencies by the series inductance and resistance of the connecting leads and of the measuring capacitor. It accomplishes this by using a coaxial go-and-return path to the specimen, and by maintaining these inductances and resistances relatively constant, whether the test specimen is in or out of the circuit.

**C-6.2 Method** -- In this method., the specimen which is either the same size as, or smaller than, the electrodes is clamped between the electrodes. Unless the surfaces of the specimen and electrodes are lapped or ground very flat, metal foil or its equivalent shall be applied to the specimen before it is placed in the electrode system. Upon removal of the specimen, the electrode system may be made to have the same capacitance by moving the micro. meter electrodes closer together.

C-6.2.1 When the micrometer electrode system is carefully calibrated for capacitance changes, its use eliminates the corrections for edge capacitance, ground capacitance, and connection capacitance. A disadvantage is that the capacitance calibration is not as accurate as that of a conventional variable multiple plate capacitor, and also it is not direct reading. However, at frequencies below 1 Mc/s, where the effect of series inductance and resistance in the leads is negligible, the capacitance calibration of the micrometer electrodes may be replaced by that of a standard capacitor in parallel with the micrometer electrode system. The change in capacitance with the specimen in and out is measured in terms of this capacitor.

C-6.2.2 The specimen is first clamped between micrometer electrodes and the network used for measurement, is tuned. The specimen is then removed, and the total capacitance in the circuit is restored to its original value either by moving, the micrometer electrodes closer together or by readjusting the standard capacitor.

Capacitance  $C_p$  of the specimen is calculated according to Appendix B.

The dissipation factor

$$\tan \delta_1 = ( \Delta C_1 - \Delta C_o ) / 2 C_p \quad \dots\dots\dots (27)$$

where  $\Delta C_1$  and  $\Delta C_o$  are the relevant differences of the two capacitance readings at both sides of the resonance setting of the variable capacitor  $M_2$  ( see Fig. 2 ), the specimen being in place or removed respectively, yielding voltages at the detector input according to  $\sqrt{2}/2$  of the relevant resonance voltages. Care is to be taken that the test frequency remains unchanged during this procedure.

**NOTE** — The resistance of the electrodes applied to the specimen becomes appreciable at high frequencies and causes a spurious increase in dissipation factor if the specimen



is not flat or of uniform thickness. The frequency at which this becomes noticeable depends on the surface flatness of the specimen, but it may be as low as 10 Mc/s. Additional measurements of capacitance and dissipation factor shall therefore be made at frequencies of 10 Mc/s and upwards on the specimen with no electrodes. If  $C_W$  and  $\tan \delta_W$  are the capacitance and dissipation factor of the specimen with no electrodes, the true dissipation factor is

$$\tan \delta = \frac{C_p}{C_W} \tan \delta_W \dots\dots\dots (28)$$

where  $C_p$  is the capacitance of the specimen with electrodea.

**C-6.3** A source of minor error in a micrometer electrode system is that the edge capacitance of the electrodes, which is included in their calibration, is slightly changed by the presence of a dielectric having the same diameter as the electrodes.

This error may be practically eliminated by making the diameter of the specimen less than that of the electrodes by twice its thickness.

## APPENDIX D

### ( Clause 11.3 )

#### ACCURACY TO BE EXPECTED IN THE METHODS OF MEASURING CAPACITANCE AND ac LOSS

##### **D-1. ACCURACY TO BE EXPECTED**

**D-1.1** The methods outlined in 9 contemplate a degree of accuracy in the determination of permittivity of  $\pm 1$  percent and of dissipation factor  $\pm (5 \text{ percent} + 0.0005)$ . These accuracies depend upon at least three factors :

- a) The accuracy of the observations for capacitance and dissipation factor,
- b) The accuracy of the corrections to these quantities caused by the electrode arrangement used, and
- c) The accuracy of the calculation of the direct interelectrode vacuum capacitance ( see Appendix A ).

##### **D-2. ACCURACY FOR OBSERVATION OF CAPACITANCE AND DISSIPATION FACTOR**

**D-2.1** Under favourable conditions and at the lower frequencies, capacitance may be measured with an accuracy of  $\pm (0.1 \text{ percent} + 0.02 \text{ pF})$  and dissipation factor of  $\pm (2 \text{ percent} + 0.0005)$ . At the higher frequencies

these limits may increase for capacitance to  $\pm (0.5 \text{ percent} + 0.1 \text{ pF})$  and for dissipation factor to  $\pm (2 \text{ percent} + 0.0002)$ .

### **D-3. DIELECTRIC SPECIMENS PROVIDED WITH A GUARD ELECTRODE**

D-3.1 These are subject only to an error in the calculation of the direct interelectrode vacuum capacitance. The error caused by too wide a gap between the guarded and the guard electrodes generally amount to several tenths percent, and the correction may be calculated to a few percent of itself. The error in measuring the thickness of the specimen may amount to a few tenths percent for an average thickness of 1.6 mm on the assumption that it may be measured to  $\pm 0.005$  mm. The diameter of a circular specimen may be measured to an accuracy of  $\pm 0.1$  percent, but enters as the square. Combining these errors, the direct interelectrode vacuum capacitance may be determined to an accuracy of  $\pm 0.5$  percent.

**D-3.2 Capacitance of Specimens with Electrodes Applied to the Surface, Measured with Micrometer Electrodes**—These need no corrections other than that for direct interelectrode capacitance, provided the specimens are sufficiently smaller in diameter than the micrometer electrodes. When two-terminal specimens are measured in any other manner, the calculation of edge and ground capacitance shall involve considerable error, since each may be from 2 to 40 percent of the specimen capacitance. With the present knowledge of these capacitances, there may be a 10 percent error in calculating the edge capacitance and a 25 percent error in evaluating the ground capacitance. Hence the total error involved may be from several tenths to a few percent. However, when neither electrode is grounded, the ground capacitance error is greatly reduced.

**D-3.3 With Micrometer Electrodes** — It is possible to measure dissipation factor of the order of 0.03 to within  $\pm 0.0003$  of the true value and dissipation factor of the order of 0.0002 to within  $\pm 0.00005$  of it. The range of dissipation factor is normally 0.0001 to 0.1 but may be extended above 0.1. Between 10 and 20 Mc/s it is possible to detect a dissipation factor of 0.00002. Permittivities from 1 to 5 may be measured to  $\pm 2$  percent of the true value. The accuracy is limited by the accuracy of the measurements required in the calculation of direct interelectrode vacuum capacitance and by errors in the micrometer electrode system.

# INTERNATIONAL SYSTEM OF UNITS (SI UNITS)

## Base Units

Quantity	Unit	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

## Supplementary Units

Quantity	Unit	Symbol
Plane angle	radian	rad
Solid angle	steradian	sr

## Derived Units

Quantity	Unit	Symbol	Definition
Force	newton	N	1 N = 1 kg.m/s <sup>2</sup>
Energy	joule	J	1 J = 1 N.m
Power	watt	W	1 W = 1 J/s
Flux	weber	Wb	1 Wb = 1 V.s
Flux density	tesla	T	1 T = 1 Wb/m <sup>2</sup>
Frequency	hertz	Hz	1 Hz = 1 c/s ( s <sup>-1</sup> )
Electric conductance	siemens	S	1 S = 1 A/V
Electromotive force	volt	V	1 V = 1 W/A
Pressure, stress	pascal	Pa	1 Pa = 1 N/m <sup>2</sup>

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